**Photonic Sensors** (2011) Vol. 1, No. 1: 54‒61

DOI: 10.1007/s13320-010-0019-7 Photonic Sensors

**Review**

# Development of Fully-Distributed Fiber Sensors Based on Brillouin Scattering

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**Abstract:** Brillouin scattering based optical fiber sensors (BOFS) have the unique advantages over other sensors such as long distance, fully distributed, and multi-parameter sensing. The progresses on the development of BOFS technology in Nanjing University are reviewed. The key technologies to make BOFS with ultra-long distance, high spatial resolution, and fast measuring speed are discussed and realized.

**Keywords:** Brillouin scattering, fully distributed optical fiber sensor, Brillouin optical time domain reflectometry, strain monitoring

## 1. Introduction

The Brillouin scattering based optical fiber sensor (BOFS) can realize fully distributed strain and temperature measurement along the fiber and by one end of the fiber, which provides a convenient way for health monitoring on the large civil structures, such as dams, bridges, pipe lines, and tunnels, for which long sensing length is required to cover the entire structures in 2D or 3D. Therefore, BOFS has gained extensive attention and many BOFS systems based on optical time-domain reflectometry (BOTDR) are developed in recent years [1‒11]. However the existed BOFS systems can't meet the requirement of some specific situations. For example, the spatial resolution of measurements is limited to 1 m which is difficulty to detect crack in concrete structures, while the sensing time is usually longer than minutes which can't be used as real-time monitoring for invasion. We have focused on the improvement of performances for BOFS system including spatial resolution, measurement time, and sensing range since 2008 [12‒17]. This paper reports some novel proposals we have made.

## 2. Improvement of spatial resolution

Since the spatial resolution of BOFS is limited to 1 m by the phonon life time of 10 ns[18], the application of BOFS in structural health was limited. We proposed a novel multi-Lorentz fitting method based on equivalent optical pulse (EOP) to improve the spatial resolution. In this method, the EOP is defined as a nominal optical pulse which is obtained by integrating the probe optical pulse over the time to accomplish one single sampling. So the Brillouin signal obtained in one single sampling can be treated as if a Brillouin signal generated by the EOP and received by the system within infinite short time. The received Brillouin backscattered spectrum (BBS) of EOP is decomposed into sub-BBS's according to the shape of EOP. Then the BBS is fitted by multi-Lorentz function to obtain central frequency of each sub-BBS. The strain/temperature in the

Received: 9 October 2010 / Revised version: 8 November 2010

length corresponding to each sub-BBS can be obtained by use of the dependence of Brillouin frequency shift on strain /temperature.

The BBS received by the receiver contains the total information generated by probe pulse light (PPL) in the fiber corresponding to a half length of PPL. But it takes time to receive BBS due to the restriction of analog-to-digital (A/D) converter's sampling rate. Thus the received BBS is an integration of BBS over the half length of PPL and the half length which the PPL transmits in the receiving time. So the EOP should be considered as the integration of probe pulse when it transmits along the fiber in the receiving time.

The probe pulse is assumed as an ideal rectangular pulse described as

$$y_0(t)=\begin{cases}A & (t_0 \le t \le t_0+\tau)\\ 0 & (t<t_0 \text{ or } t>t_0+\tau)\end{cases} \tag{1}$$

where $\tau$ is the pulse width. If the receiving time needed for A/D converter to complete one single sampling is $\tau'$, according to the difference between the pulse width and the receiving time, the corresponding EOP's are described as (2) and (3), respectively and shown in Fig. 1.

(a) if $\tau \ge \tau'$:

$$y(t)=\begin{cases}A(t-t_0) & (t_0 \le t < t_0+\tau')\\ A\tau' & (t_0+\tau' \le t \le t_0+\tau)\\ A\tau' - A(t-t_0-\tau) & (t_0+\tau < t \le t_0+\tau+\tau')\\ 0 & \text{(others)}\end{cases} \tag{2}$$

(b) if $\tau \le \tau'$:

$$y(t)=\begin{cases}A(t-t_0) & (t_0 \le t < t_0+\tau)\\ A\tau & (t_0+\tau \le t \le t_0+\tau')\\ A\tau - A(t-t_0-\tau') & (t_0+\tau' < t \le t_0+\tau+\tau')\\ 0 & \text{(others)}\end{cases} \tag{3}$$

It is shown that the width of the EOP is $\tau+\tau'$, and the corresponding spatial resolution is

$$\Delta z' = \frac{c(\tau+\tau')}{2n}. \tag{4}$$

The BBS can be described as a Lorentzian curve, which is given as

$$g(\upsilon,\upsilon_B)=\frac{p_0(\omega/2)^2}{(\upsilon-\upsilon_B)^2+(\omega/2)^2} \tag{5}$$

where $\upsilon$ is the frequency of BBS, $\upsilon_B$ is the central frequency, $p_0$ is the peak power, and $\omega$ is the full width at half maximum (FWHM).

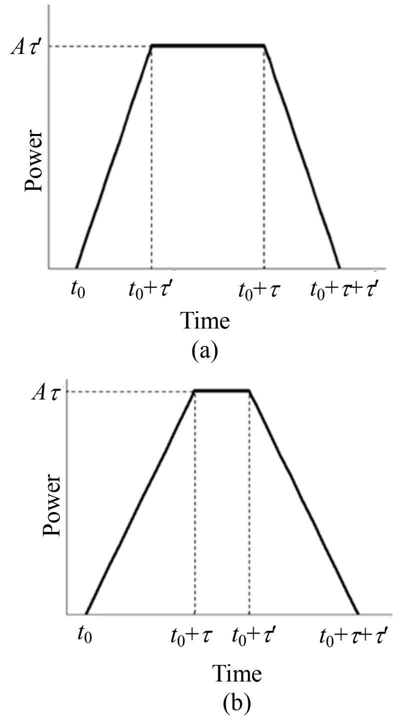


Fig. 1 (a) Equivalent optical pulse when $\tau \ge \tau'$ and (b) equivalent optical pulse when $\tau \le \tau'$.

As the BBS contains the total information generated by PPL in the fiber corresponding to a half length of PPL, the PPL can be equally divided into *m* segments and the BBS can be seen as the sum of $\text{BBS}_i$ generated by $\text{PPL}_i$ in different sections of fiber within the spatial resolution, where *i* means different subscripts of BBS and PPL from 1 to *m*. If strain distribution within the spatial resolution is non-uniform, the BBS will be distorted. The distorted BBS can be described as the following equation:

$$g(\upsilon,\upsilon_B)=\sum_{i=1}^{m} g_i(\upsilon,\upsilon_{Bi})=\sum_{i=1}^{m}\frac{p_i(\omega_i/2)^2}{(\upsilon-\upsilon_{B_i})^2+(\omega_i/2)^2} \tag{6}$$

where $g_i(\upsilon,\upsilon_{Bi})$ is the BBS*i*, $\upsilon_{Bi}$ is the central frequency of BBS*i*, $p_i$ is the peak power of BBS*i*, and $\omega_i$ is the FWHM of BBS*i*.

When $\upsilon_{Bi}$ and $\omega_i$ are the same with $\upsilon_B$ and $\omega$, and the strain/temperature is constant, it is easily to obtain $p_i$ according the ratio of $p_i$ and $p$, as long as the shape of the equivalent optical pulse is known.

If the strain at one section of fiber is different from others and the length of the section is shorter than the width of EOP, $p$ and $\omega$ change little with the strain. Therefore, it is feasible to consider they are constant, so we could obtain each $v_{Bi}$ by iterative fitting from the section where the strain is known. At last, the strain curve along the fiber is obtained and the spatial resolution increases to $\frac{c(\tau+\tau')}{2mn}$. In order to perform the iterative fitting process, the length of the divided fiber unit must be integer multiple of the sampling length.

The experimental result demonstrates that the spatial resolution for strain measurement is improved to 0.05 m by multi-Lorentz fitting method based on EOP [12].

## 3. Increase of measuring speed

Conventional BOFS system based on spontaneous BBS narrow-band detection is not only time-consuming but also controlling complicated in frequency-scanning. In addition, the weak spontaneous Brillouin scattered signals need to be averaged over thousands times to achieve the needed signal-to-noise ratio. Thus the time to complete a measurement generally requires tens minutes. We proposed several new methods to increase the measuring speed and make real-time monitoring in the past years [16, 17].

### 3.1 Wideband detection of Brillouin scattering spectrum

The schematic diagram of BBS wideband detection system is shown in Fig. 2.

A double-balanced photodetector with a 1 GHz bandwidth is used as the wideband receiver to transform the whole beat optical signals into an electrical signal. A high-speed A/D converter with a 1 GHz bandwidth is used to convert analogue signals received from the photodetector to digital signals. The obtained signals are divided into sections according to the duration of probe pulse, and then each of them is transformed by discrete Fourier transform (DFT). As each of the signal-section is corresponding to a section of length along the sensing fiber, the power spectrum obtained by DFT just stands for the BSS that is generated when the probe pulse passes through the corresponding fiber section. By gathering all the BSS units along the sensing fiber, we can obtain a three-dimensional BSS, which includes distance, frequency, and power information. By fitting a Lorentzian function to each BSS, the Brillouin frequency shift and power change are deduced from the fitted curve. Temperature/strain change along the sensing fiber is determined by analyzing the frequency shift and power change of the total BSS.

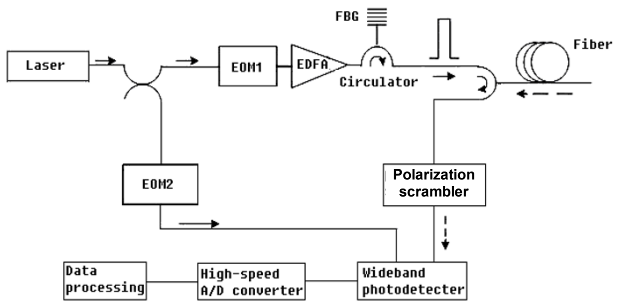


Fig. 2 Schematic configuration of BOTDR system used for wideband detection of BBS.

The spatial resolution of the proposed BOFS system is determined by

$$\delta z = \max\{\frac{cW}{2n}, \frac{cN}{2nf_S}\} \tag{7}$$

where $c$ is the speed of light in vacuum, $n$ is the refractive index of fiber core, $w$ is the pulse width, $N$ is the number of DFT points, and $f_S$ is the sampling rate of high-speed A/D converter.

As the proposed BOFS system doesn't need the process of scanning, the total measurement time is at least one order of magnitude smaller than that of the narrow-band detection BOFS system, though the data processing time of the proposed system may be a little longer than that of conventional system.

In order to test the effective of the proposed BSS wideband detection method, a distributed temperature measurement experiment is conducted. The total sensing length is made up of three sections of fiber fusion spliced together and arranged as shown in Fig. 3.

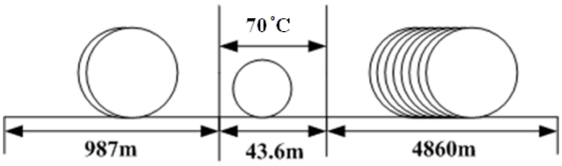

Fig. 3 Configuration of the sensing fiber in the experiment.

Figure 4 shows Brillouin frequency shift of the heated section of the fiber. Because in the experiment the pulse width was 20 ns and the sampling rate was 4 G Sa/s, the number of sampling points was 80. The refractive index of the core of standard single mode fiber was 1.46. Therefore, the spatial resolution of BOTDR system in the experiment was about 2 m according to (7). In Fig. 5 it could be seen that the length of the heated fiber was 44 m, which was in good agreement with the actual value of 43.6 m. According to the relationship between temperature and Brillouin frequency shift, the temperature of the heated fiber was 69.8 ℃, which was in good agreement with actual value of 70 ℃.

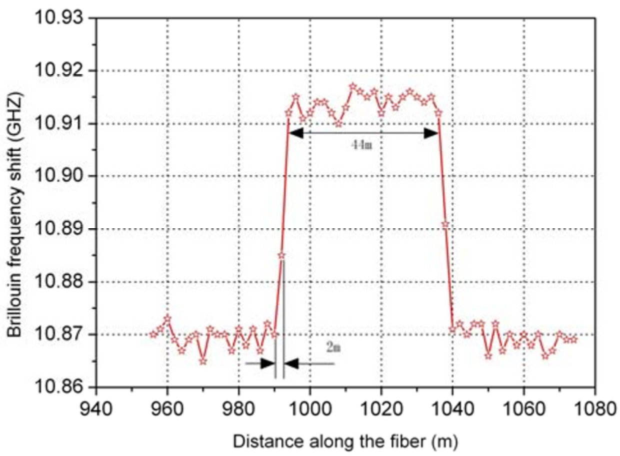

Fig. 4 Brillouin frequency shift of the heated section of the fiber.

BOTDR system based on SBSS wideband detection method has been demonstrated for a 6 km fiber, and a temperature resolution of 3 ℃ and a spatial resolution of 2 m have been achieved. The measurement time is only about one-tenth that of conventional narrow-band detection method.

### 3.2 Real-time spectrum analysis

Figure 5 shows the configuration of real-time spectrum analysis module.

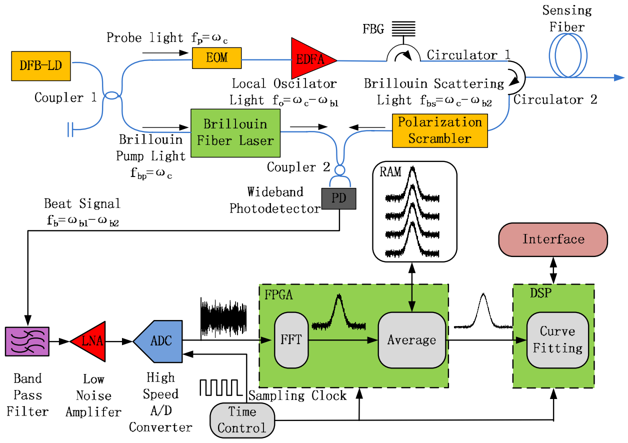

Fig. 5 Configuration of BOFS system based on real-time spectrum analysis.

Unlike the conventional BOFS system, the new method captures the whole frequency spectrum at one time rather than sweeping and measuring the spectrum from point to point. A narrow band distributed feedback laser diode (DFB-LD) with the center frequency of $\omega_c$ is used as light source. The light source is divided into two parts by coupler 1. The first part is the probe light which is encoded by electrical optical modulator (EOM) and amplified by Erbium-doped fiber amplifier (EDFA). A fiber Bragg grating (FBG) and a circulator are used to filter the wide band noise of EDFA. The encoded light is then injected into the sensing fiber through circulator 2. The second part of light source acts as a pump light to stimulate a Brillourin fiber laser. The fiber laser generates a local oscillator with center frequency of $f_{lo}=\omega_c-\omega_{b1}$. The back scattering signal from circulator 2 passes through a polarization scrambler to get uniform distributed polarization state. The center frequency of the back scattering signal is $f_{bs}=\omega_c-\omega_{b2}$. With coherent detection, the photo detector produces an electronic beat signal with center frequency of $f_b=\omega_{b1}-\omega_{b2}$.

After passing through the band pass filter and low noise amplifier, the beat signal is sampled by a 2.5 GHz high speed A/D converter. The obtained time domain data is divided into groups and transformed to frequency domain with fast Fourier transform (FFT). Since single measurement's signal to noise ratio (SNR) is relatively low, average is needed to improve the SNR. All the FFT and average operations are done within a field programmable gate array (FPGA) device. As each group is corresponding to a section of length along the sensing fiber, the power spectrum obtained by FFT stands for the BBS that is generated during the probe pulse passes through the corresponding fiber section. Brillouin frequency shift and power change are deduced from curve fitting with Lorentzian function. The temperature/strain change along the sensing fiber is determined by analyzing the frequency shift and power change. A high speed digital signal processor (DSP) is used to do the curve fitting and data analyzing while maintaining the human-computer interface.

At least three advantages can be achieved with real-time spectrum analysis. First of all, since the proposed method doesn't need the process of frequency-scanning, the total measurement time is at least one order of magnitude smaller than that of traditional detection system. Although the total data processing amount of the proposed system is much larger than the conventional one, it can be solved with pipeline and parallel processing techniques. The second advantage is that the system's ability for capturing transient events is improved which can monitor rapidly changed signal. The third one is that the reliability of the system is enhanced since the complication of the detection system is reduced by abandoning the frequency-scanning components.

Contrast experiments are performed to verify our detection method's performance. The total sensing fiber is set up with three sections of fusion spliced fibers as shown in Fig. 6. The second section's temperature is controlled with a heater during the measurement. The heater is oscillating with a period of 90 s. The pulse width is 10 ns and group size for FFT is 256 points. Thus the spatial resolution is approximate 10 m. Figure 7 shows the Brillouin frequency shift of the heated section of the fiber obtained with conventional method.

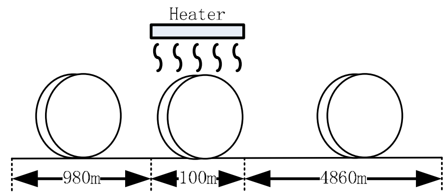


Fig. 6 Experimental setup.

The trace in Fig. 7 shows a 40 MHz frequency shift of the heated section. However we can't see the oscillating process of the temperature since frequency-scanning is used which will cause dead zone during the measurement.

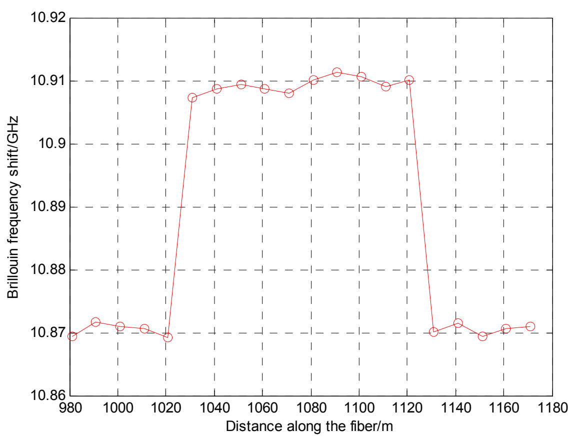


Fig. 7 Experimental result of conventional method.

Figure 8 shows the results obtained with the real-time spectrum analysis. During the same time, the proposed method completed 9 times measurements, which clearly displayed the temperature oscillating. The measured oscillating period is about 91.2 s, which is in good agreement with the actual value. In practice, the fluctuation of temperature for the sensing fiber is a hint of the outside environment's fierce change which can act as an early warning for structure healthy monitoring.

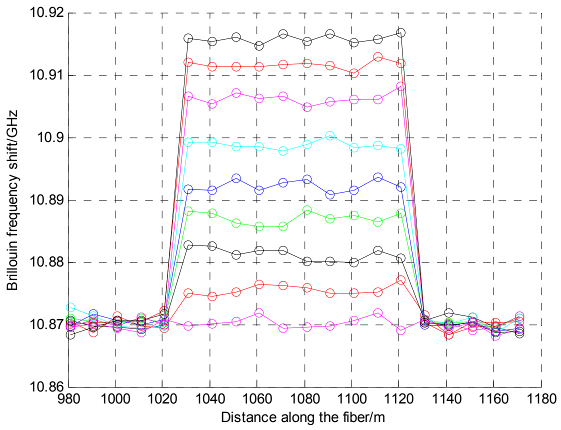


Fig. 8 Experimental result of proposed method.

## 4. Enhancement of sensing range

The sensing range of BOFS is highly determined by the SNR of the obtained Brillouin signal. Thus a long pulse which can provide higher Brillouin back scattering power must be used in the sensing system. However, according to (7), long pulse will decrease the spatial resolution of BOFS. Because of the tradeoff between sensing range and spatial resolution, we proposed to use coded probe pulses to improve the SNR of the measured signal. In our experiment, Hadamard coded pulse sequences were used. They can be easily generated from a bi-polar Hadamard matrix. And the sum of the auto-correlation of Hadamard matrix rows can be expressed as delta function. Thus, when using pulses formatted into the rows of Hadamard matrix, we can restore the signals by doing the cross-correlation between the backscattered signals and their corresponding rows. It is found that the recovered signal has a higher SNR compared with the one obtained by single pulse with the same peak power. The spatial resolution of coded BOFS is determined by the pulse width of the coded sequence unit. With this method we can achieve a high spatial resolution over a long sensing range [17].

A BOFS system which employs Hadamard sequence as the probe signal to increase the SNR of the system is proposed as shown in Fig. 9. Instead of injecting a single pulse into the sensing fiber to obtain the BBS, the BBS of the fiber is measured by injecting Hadamard sequence probe pulses. When being compared with the conventional BOFS system, the same sensing range can be achieved for the proposed system by using lower peak power pulse light, without reducing the spatial resolution.

In the experiment, 7 km and 20 km SMF28 fiber are connected by a 4 km dispersion shift fiber (DSF) to constitute the sensing fiber with a length of 31 km, as shown in Fig. 10. Brillouin frequency shift of SMF28 and DSF are 10.87 GHz and 10.72 GHz, respectively, at room temperature and in loose condition. 64-bit coded pulses with unit pulse width of 500 ns and peak power of –4 dBm are used as probe pulses.

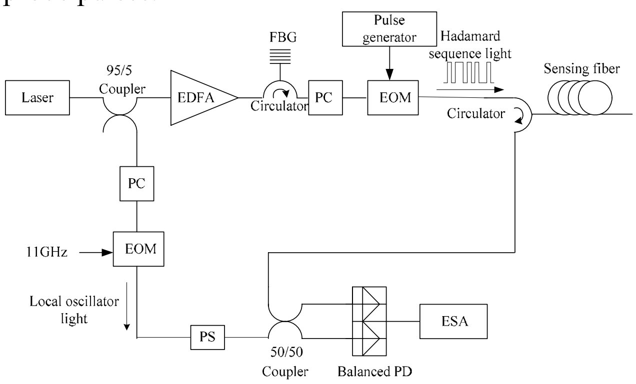


Fig. 9 Schematic diagram of the experimental setup.


Fig. 10 Configuration of the sensing fiber in the experiment.

Figure 11 shows the restored time trace of Brillouin scattering signal corresponding to the frequency of 10.87 GHz with frequency scanning method. It can be seen that three fiber sections are distinguished clearly. And the spatial resolution is 50 m corresponding to the unit pulse width 500 ns. The SNR at the fiber end is approximately 15 dB. According to the loss of the detected Brillouin signal, which is 0.4 dB/km, when the total sensing fiber length increases from 31 km to 61 km, we can still get a SNR as high as 3 dB. It indicates that the longest sensing range by use of the proposed method can be larger than 60 km.

Experimental results verify the validity of our proposed coded pulses method. The dynamic range of BOTDR system can be increased without reducing the spatial resolution by using coded pulses as the probe pulse. Further, by this means the required peak power of the probe pulse can be much lower than that of the single pulse method. Hence it can avoid the unexpected nonlinear effects in the sensing fiber caused by probe pulse with high peak power as well.

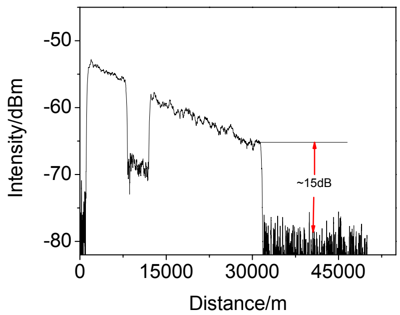


Fig. 11 Restored time trace of Brillouin scattering signal at 10.87 GHz.

## 5. Conclusions

Our work in improving the performances of BOFS system is reviewed. The improvement of spatial resolution by multi-Lorentz fitting method based on EOP, quick measurement method based on wideband detection of Brillouin scattering spectrum and real-time spectrum analysis, the enhancement of sensing range based on coded probe pulses are reported.

## Acknowledgment

This work was supported by National Basic Research Program of China (973 Program) under Grant No. 2010CB327803 and National Natural Science Foundation of China (61027617).

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